Stars as Laboratories for Nuclear Physics

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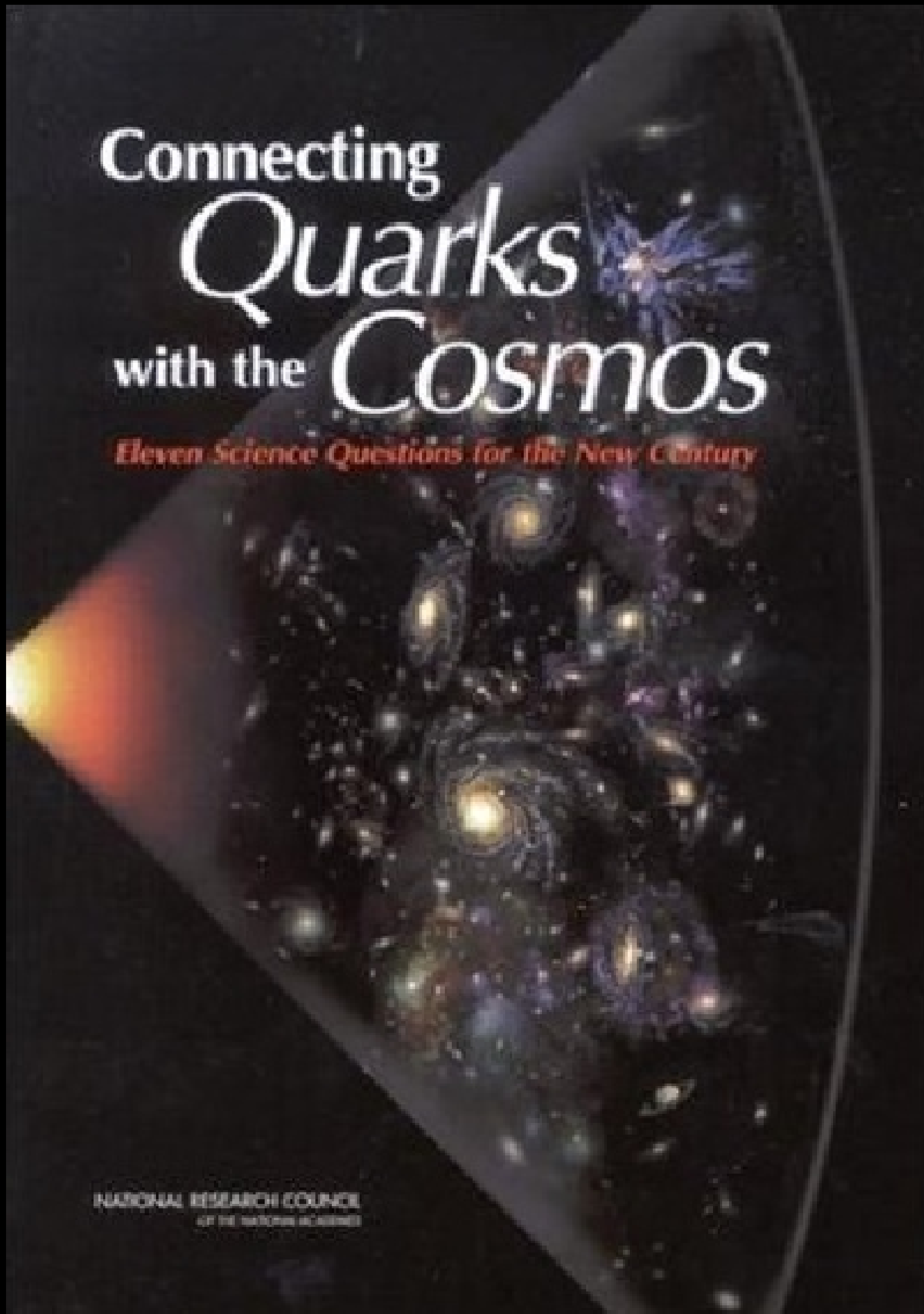
January 27, 2005

Los Alamos
NATIONAL LABORATORY
EST. 1943



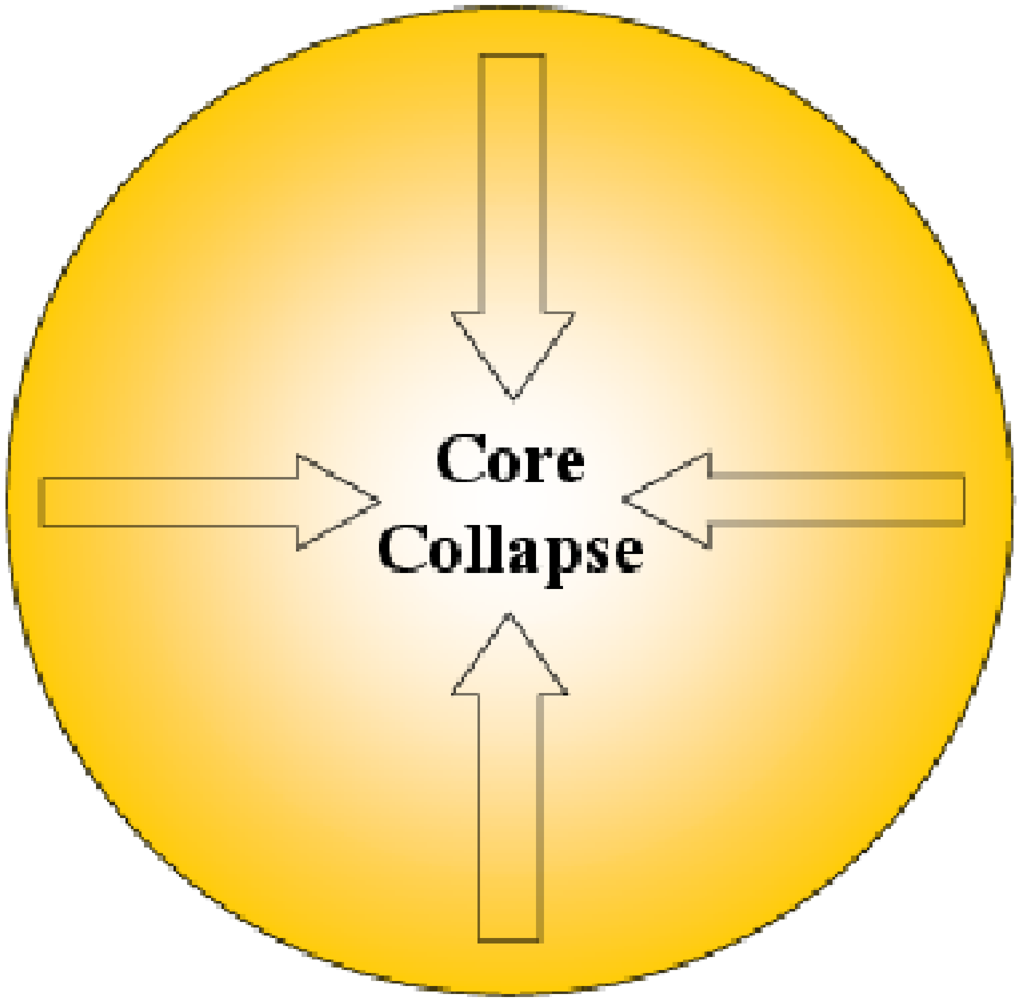
From the National Academies

We consider a few of the eleven questions:

- What Are the New States of Matter at Exceedingly High Density and Temperature?
- How Were the Elements from Iron to Uranium Made?

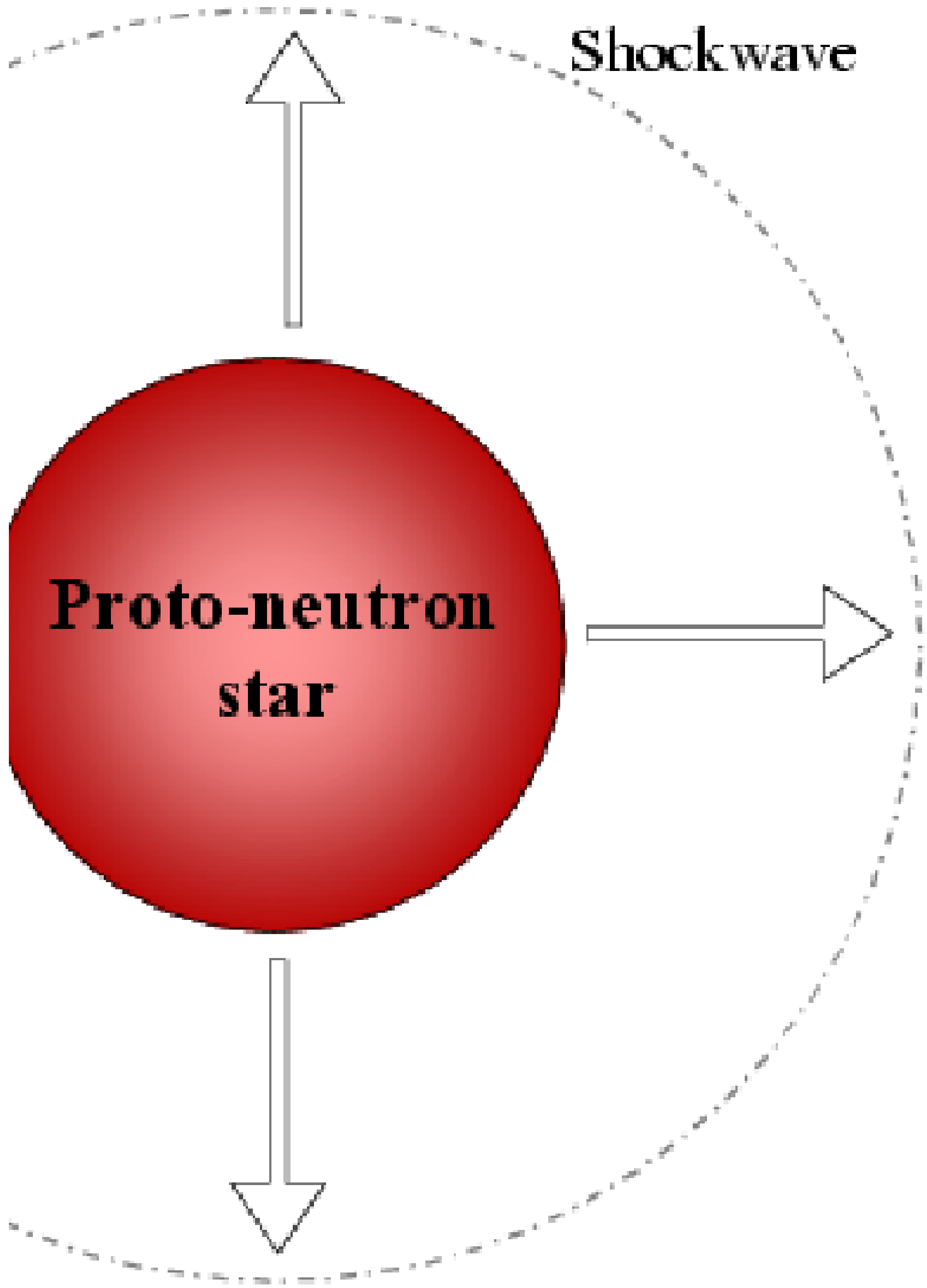
This list is not sacred
Begin with a story...

The Story - Part I



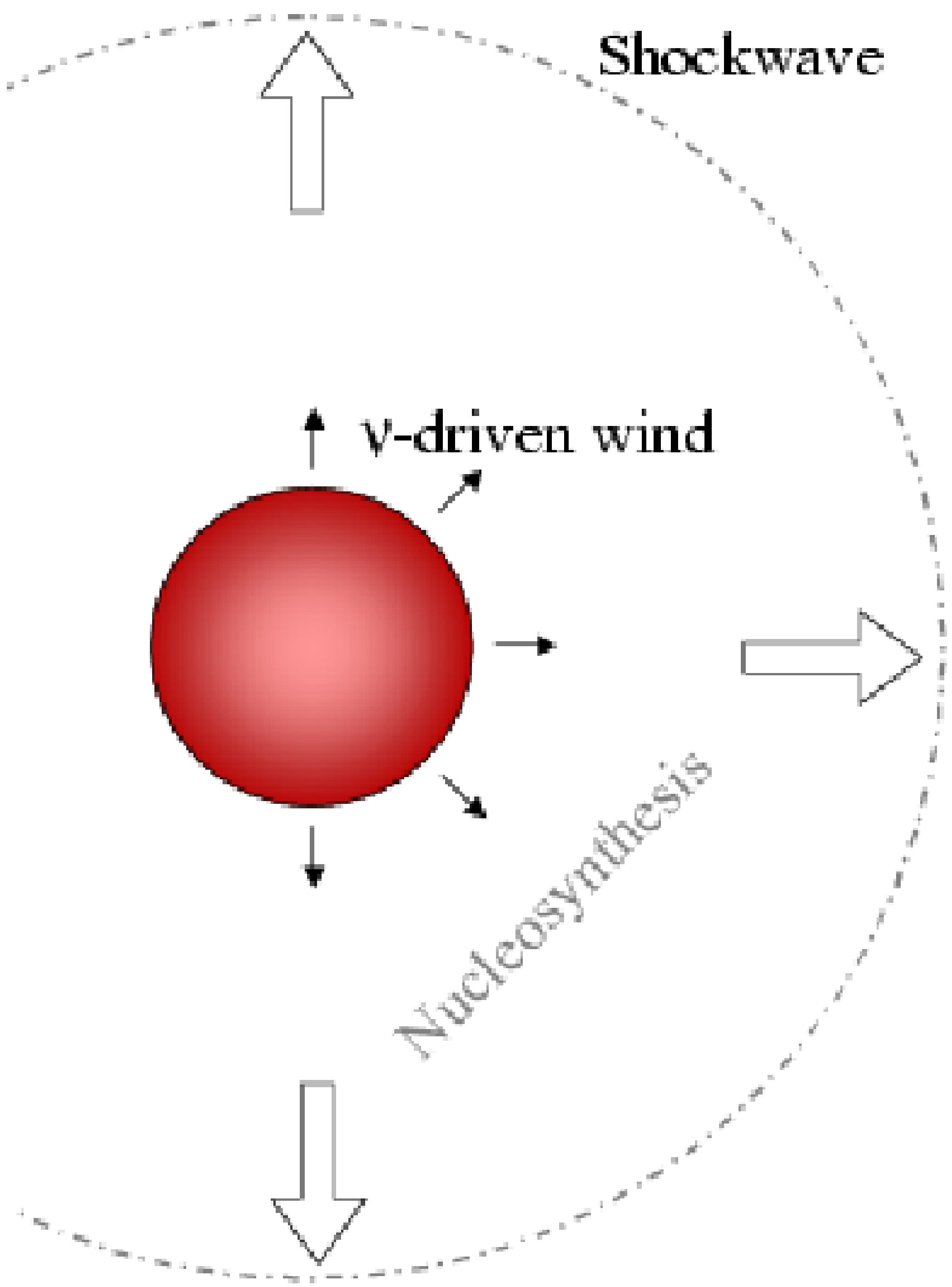
- After running out of fuel, sufficiently massive stars undergo gravitational collapse
- If the star is sufficiently massive then it forms a black hole, otherwise it may form a neutron star
- The evolution of the collapse and the evolution of the neutron star are controlled by the equation of state of matter.

The Story - Part II



- The shockwave bounces off of the the core leaving behind a hot proto-neutron star $(\mathrm{R} \sim 10\ \mathrm{km}, \mathrm{M} \sim 1.4 - 2.2\ \mathrm{M}_{\odot})$
- The neutron star cools by neutrino emission from the outer layers
- The neutrinos inside are "trapped" - the distance between collisions is much smaller than the radius of the star
- The neutrinos are trapped until for a timescale of tens of seconds - until the neutron star cools
- The trapped neutrinos tend to prohibit the formation of exotic matter, i.e. quarks, hyperons, or Bose condensates

The Story - Part III



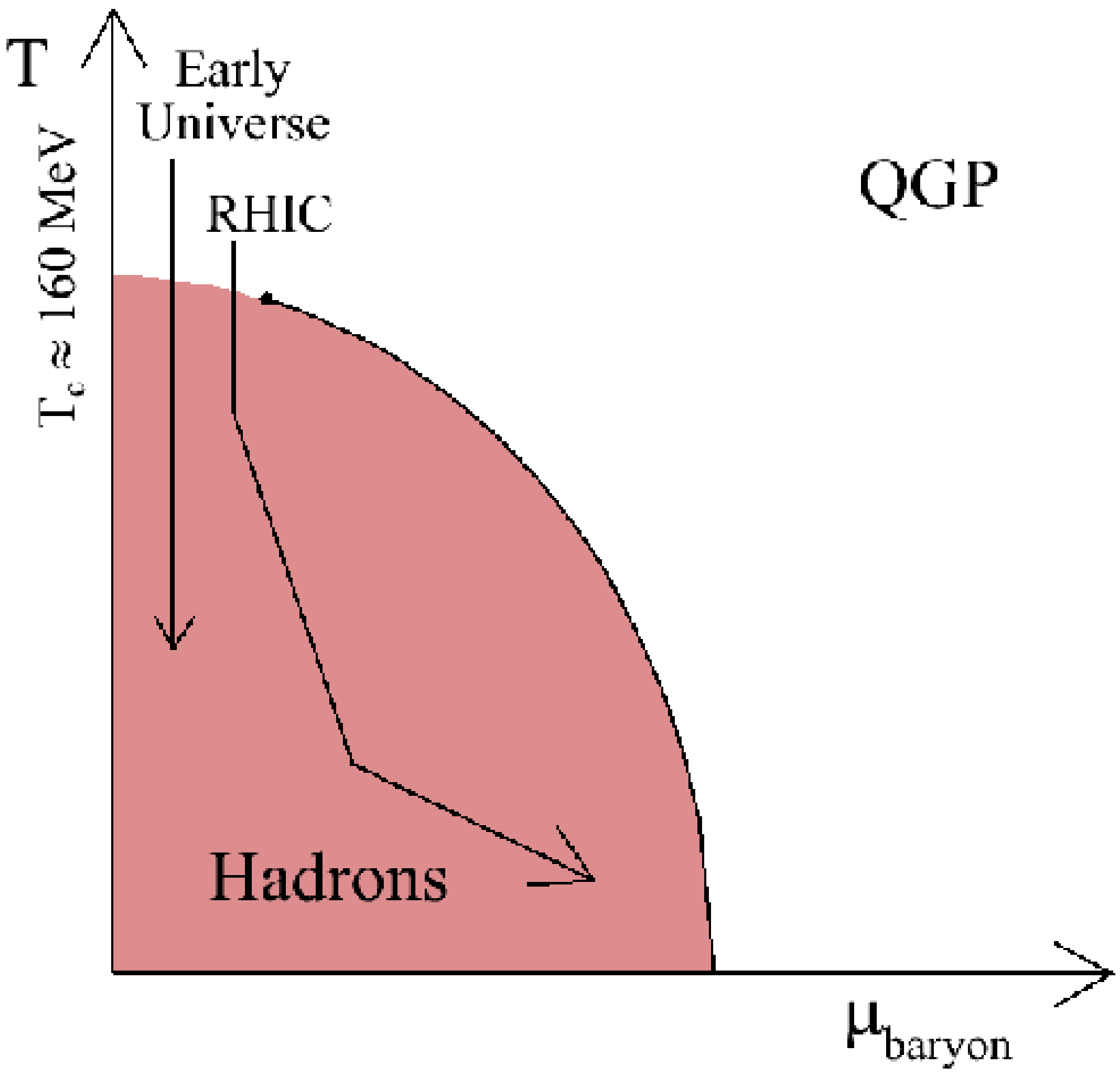
- The neutrinos deposit sufficient energy in matter behind the shockwave to form a "neutrino-driven wind"
- Inside this wind is where r-process nucleosynthesis occurs
- Now that the neutrinos are no longer trapped inside the neutron star - exotic matter may form
- The appearance of exotic matter tends to lower the maximum mass = Metastability
- The neutron star continues to cool by neutrinos for another 10^4 years

Outline of the Talk

- How these questions are being answered
  - What Are the New States of Matter at Exceedingly High Density and Temperature?
  - How Were the Elements from Iron to Uranium Made?
- Phases of matter at high density
  - What impact they have on supernovae and neutron stars
  - Relevant nuclear physics
- r-Process nucleosynthesis
- The symmetry energy
- Summarize

Matter at Extreme Density and Temperature

The Phase Diagram - Deconfinement

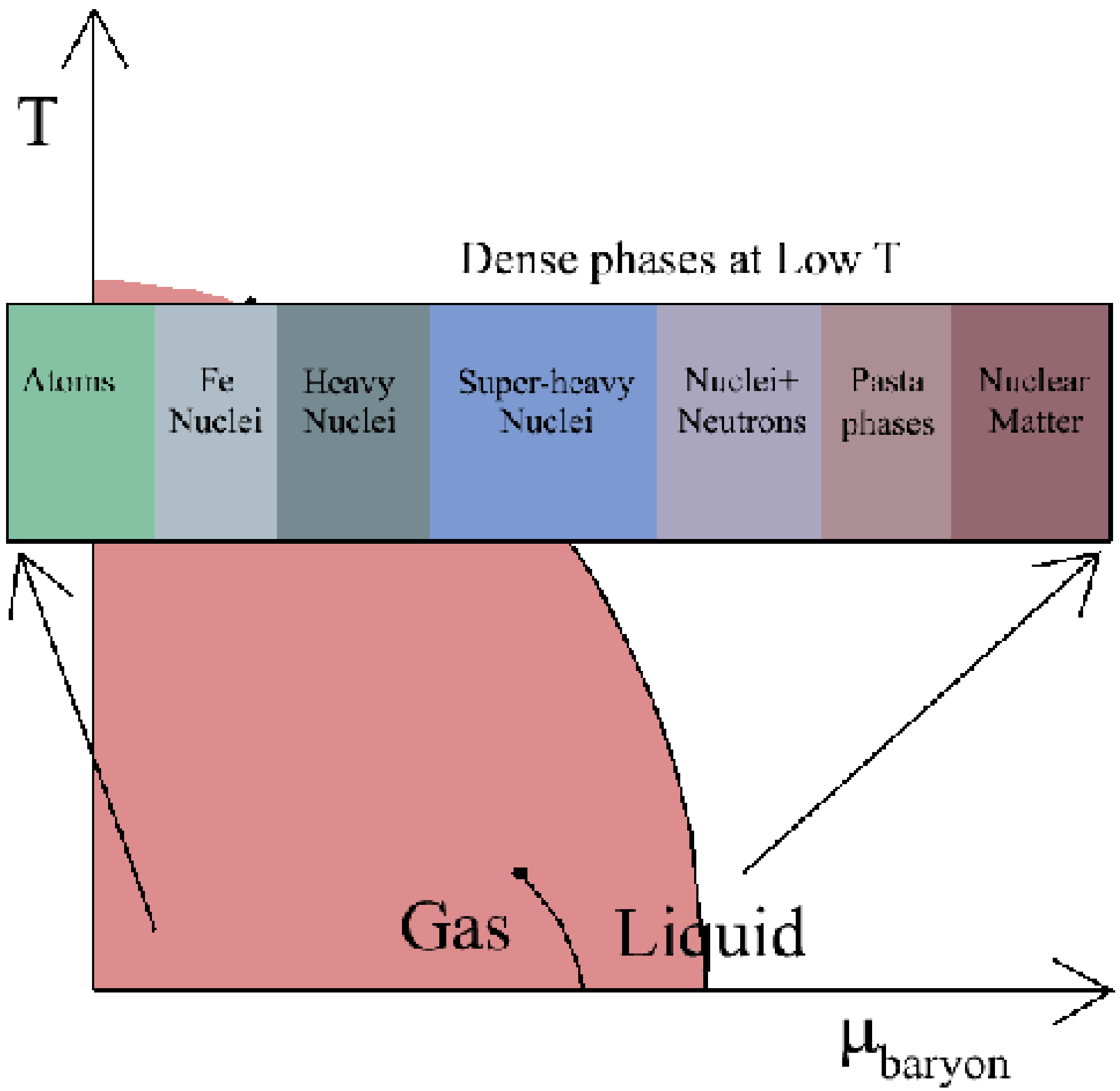


The Relativistic Heavy Ion Collider

- For sufficiently large density or temperature quarks become deconfined

Matter at Extreme Density and Temperature

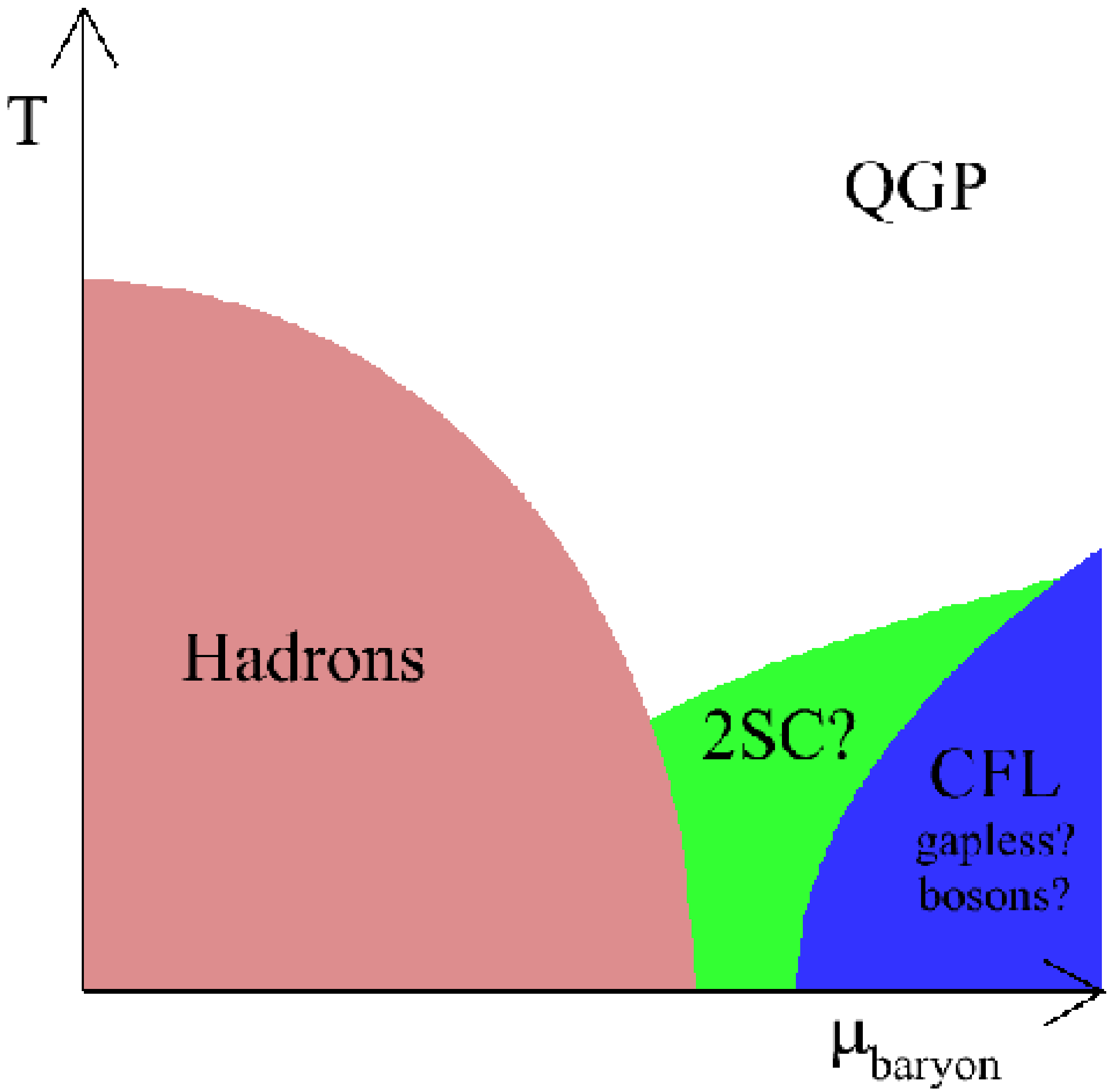
The Phase Diagram - The Liquid-Gas Phase Transition



- The phase diagram has a rich structure at moderate densities and low temperatures
- At low densities the lowest energy state consists of a gas of Fe atoms
- At higher densities, the average atomic number of nuclei increases until neutron-rich "super-heavy" nuclei dominate
- At 10^{11} g/cm^3 neutrons begin to drip out of nuclei
- Nuclei begin to be so close, that their shape is severely deformed - imagine swiss cheese
- Liquid-gas phase transition to nuclear matter
- All of these phases are explored in the late stages of stellar evolution

Matter at Extreme Density and Temperature

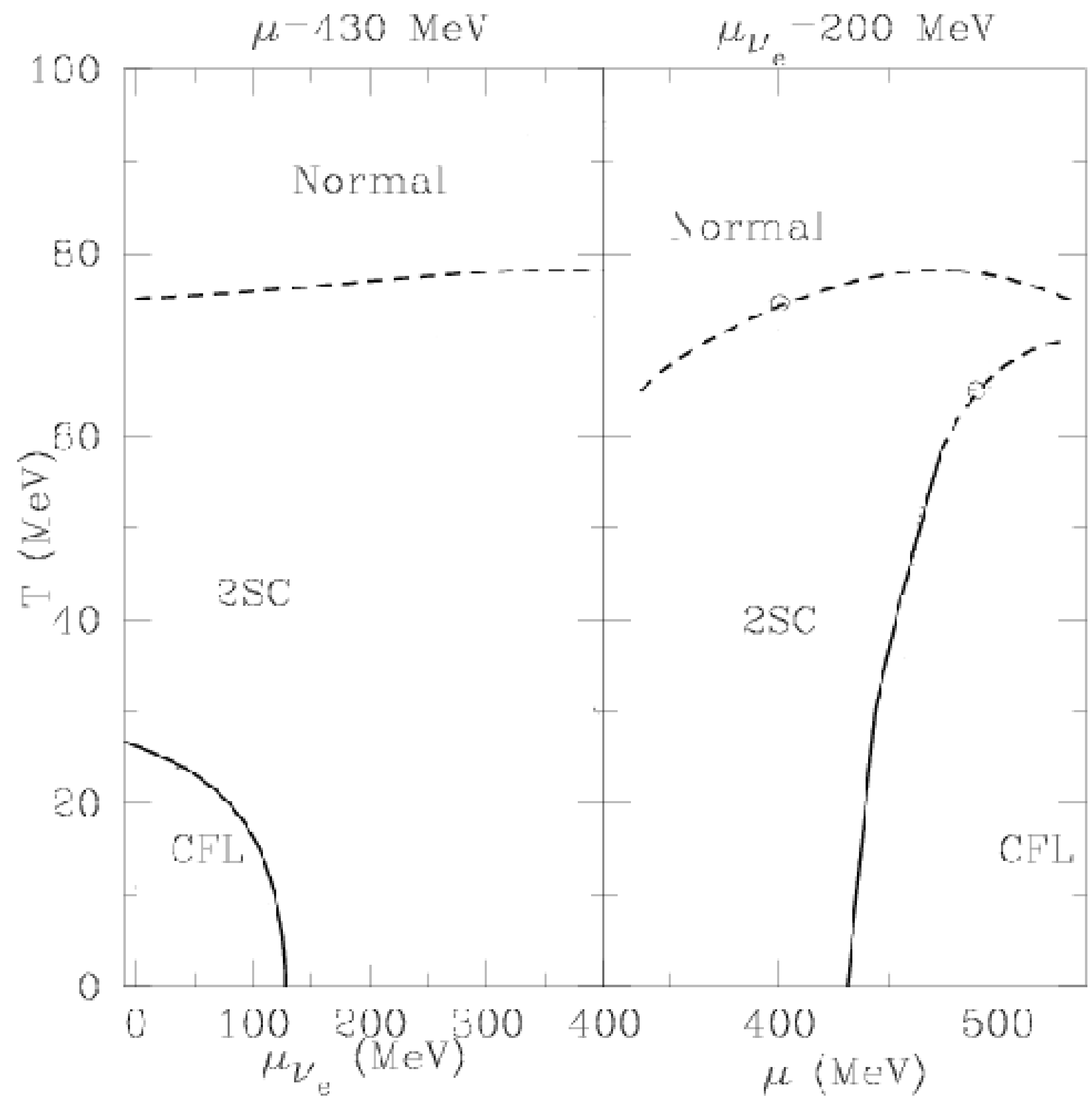
The Phase Diagram - Phases of Quark Matter



- At higher-densities and still somewhat low temperatures, strong superconductivity occurs in quark matter
- The quark-quark interaction is attractive
- 2SC phase - 4/9 quarks pair: dr-ug, dg-ur
- CFL phase - All quarks participate in the pairing
- Associated goldstone bosons and "gapless" phases

The Neutrino Contribution to the Phase Diagram

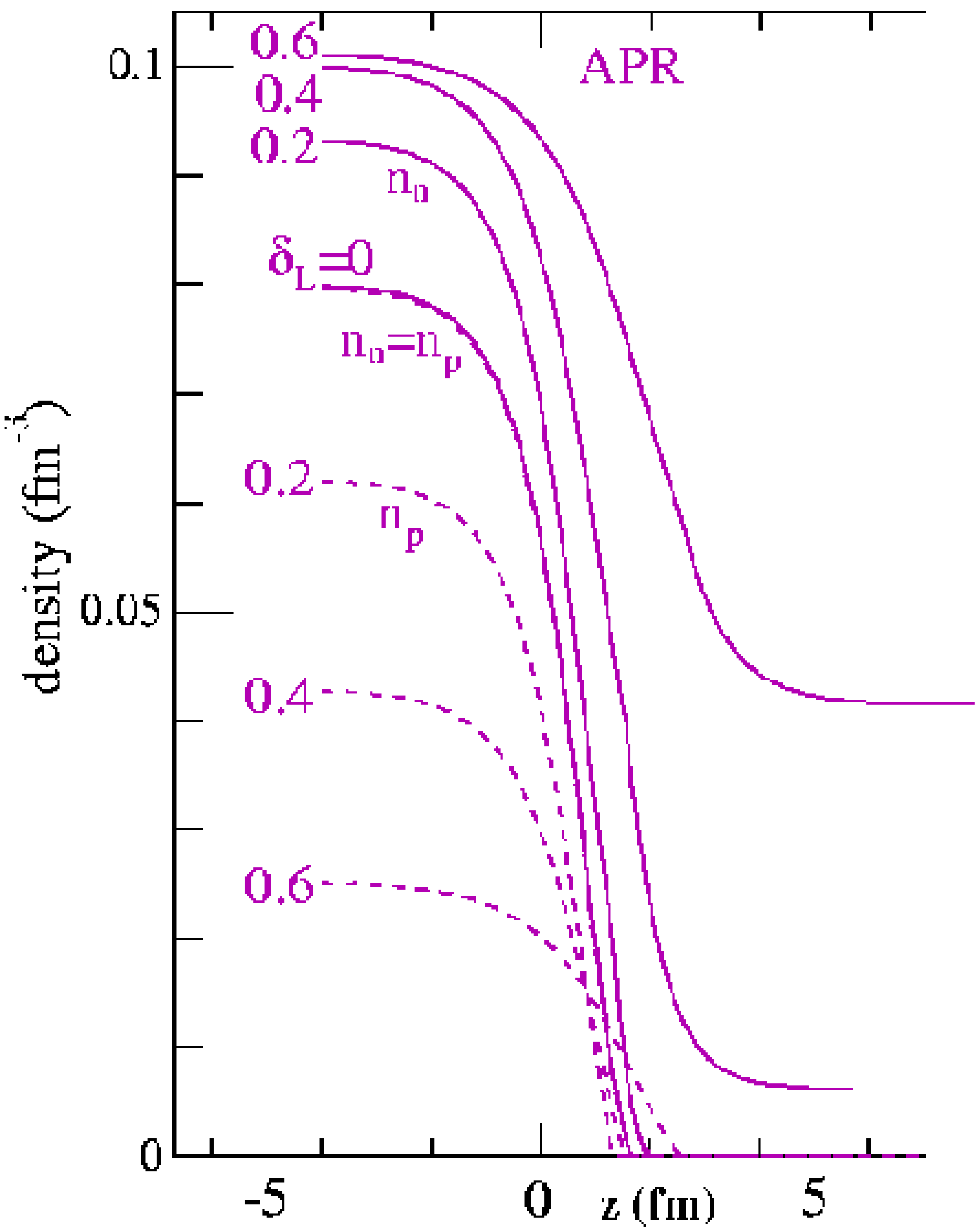
- In young neutron stars (<40 s old) neutrinos are trapped - this is the time when the emitted neutrinos can be detected on earth
- Neutrino chemical potential gives the phase diagram another dimension
- The first calculation of gapped quark matter which includes:
  - The interaction of chiral symmetry breaking and diquark condensation
  - Finite temperature
  - Flavor asymmetric matter
  - Color-neutrality
  - Finite neutrino chemical potential



Adapted from A.S., S. Reddy, and M. Prakash Phys. Rev. D 66 (2002) 094007

The Equation of State for Supernovae

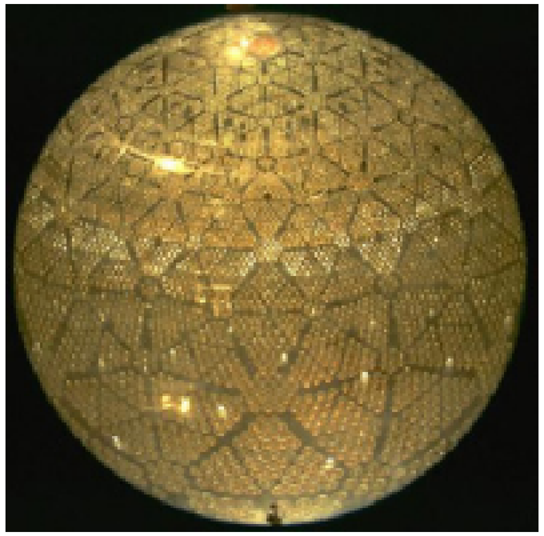
- Supernovae
  - How do we get a supernova explosion?
  - The equation of state and neutrino transport are major candidates for solving the Supernova Problem
  - The supernova explosion is likely to probe all parts of the liquid-gas phase transition previously described
  - δ_L describes the isospin asymmetry of the system
  - First calculation based on a modern ab-initio equations of state



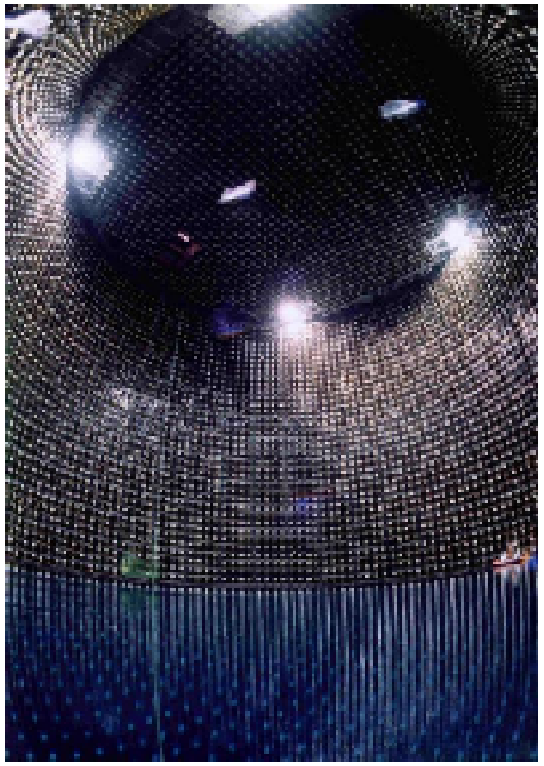
Taken from A.S., M. Prakash, J.M. Lattimer, and P.J. Ellis, Phys. Rep. (2005) in press.

Proto-Neutron Stars

- Young neutron stars
- The neutrino signal from a galactic supernova resulting in a neutron star can be detected
- Thousands of neutrinos - every 30 years or so
- Metastability - Neutron stars, if they contain an exotic component, may collapse to black holes only after the neutrinos have left
- This provides a way to discern the content of the interior
- The first study of metastability in neutron stars giving an observable prediction - Phys. Rev. Focus.

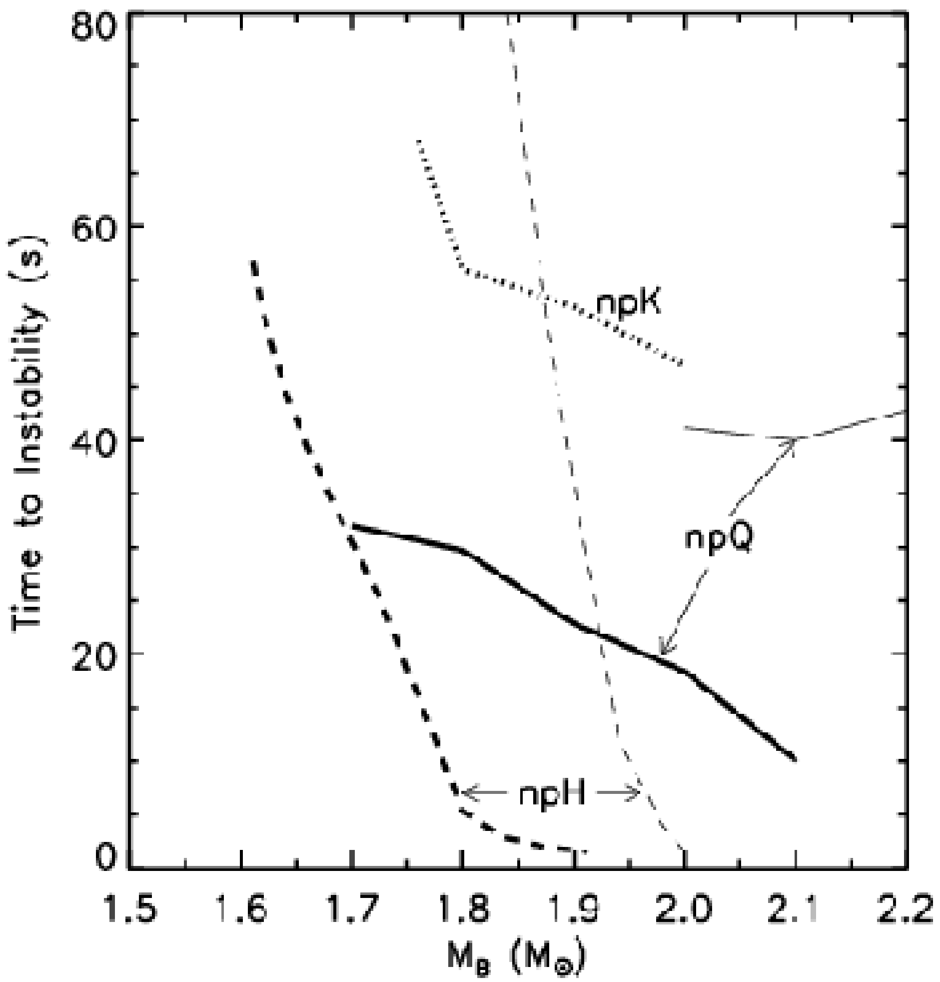


Solar Neutrino Observatory



Super-Kamiokande

More in the future?

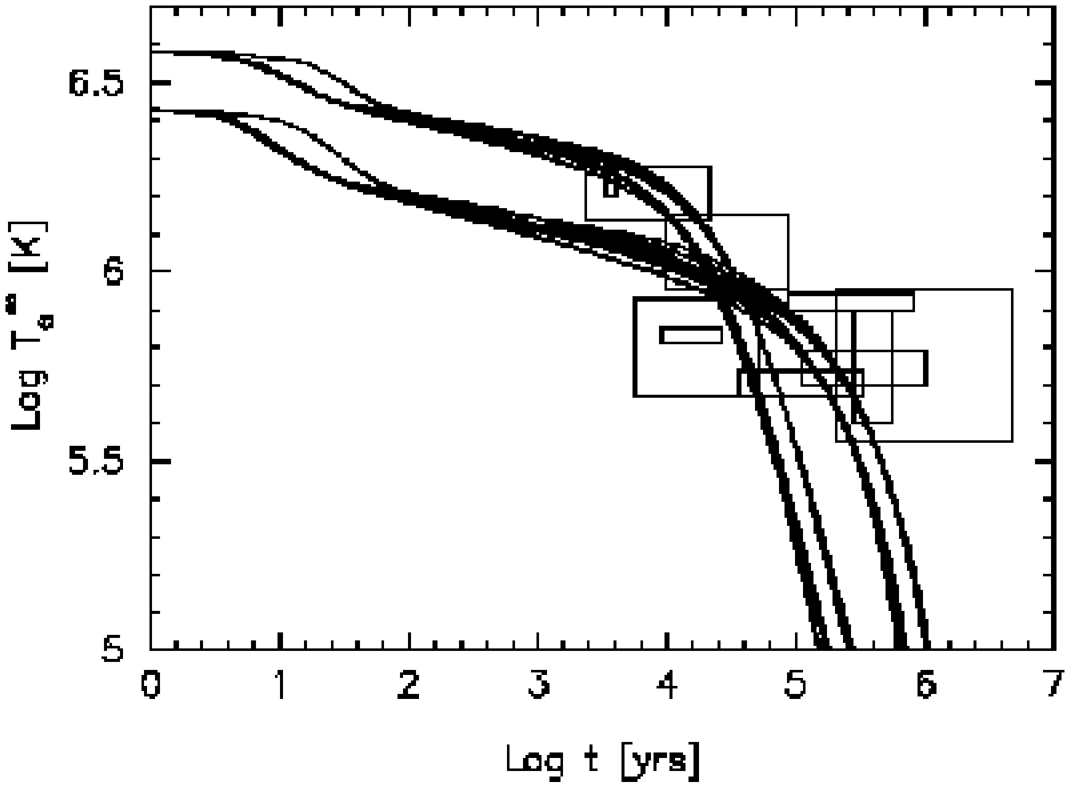


Taken from J. Pons, A. S., M. Prakash, and J.M. Lattimer, Phys. Rev. Lett. 86 (2001) 5223.

Neutron Star Cooling

X-ray (Chandra)

- Neutron star cooling is observable in X-rays for millions of years
- Age can be derived from SN associations, spin-down age
- Using the equation of state and neutrino emissivities - calculate a cooling curve
- Demonstrated that exotic forms of matter are hidden because their effect is identical to other effects. [PRL 85 (2000) 2048]
- Recent observations suggest that a few neutron stars are either too cool or too warm without "non-standard" physics [2004]



Taken from D. Page, J.M. Lattimer, M. Prakash, and A. S., Astrophys. J. Supp. 155 (2004) 623.

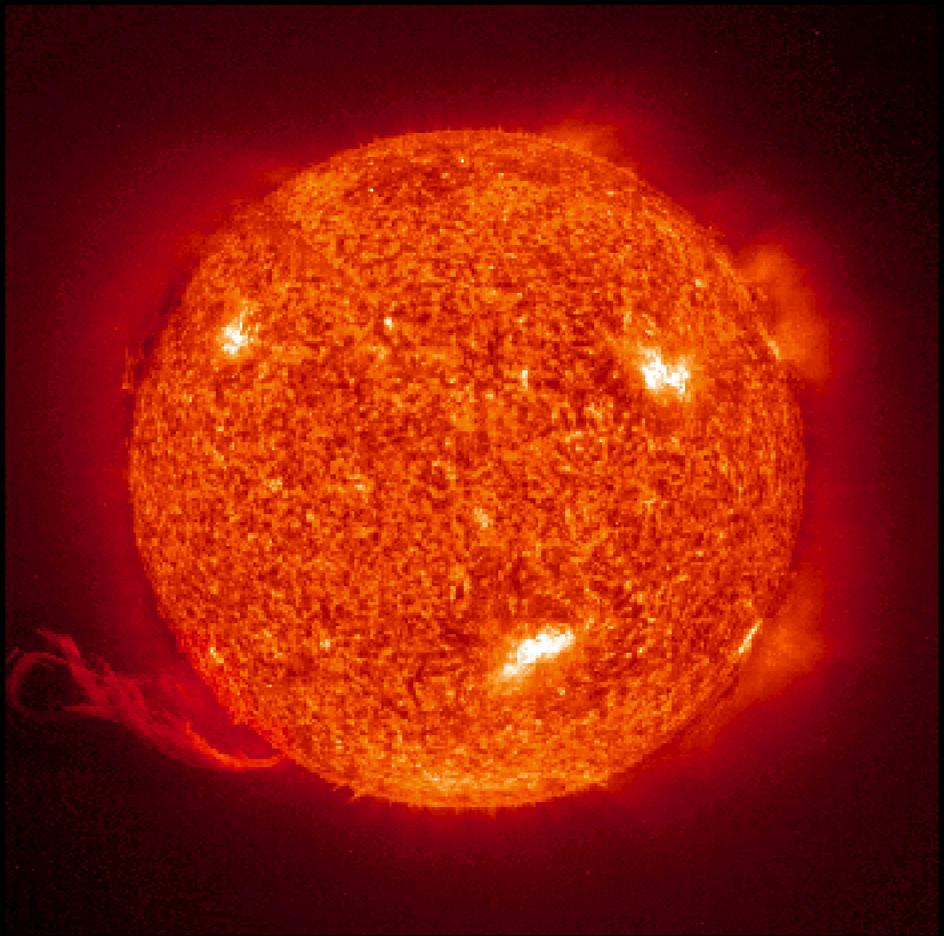
The Nuclear Physics of the Phase Diagram

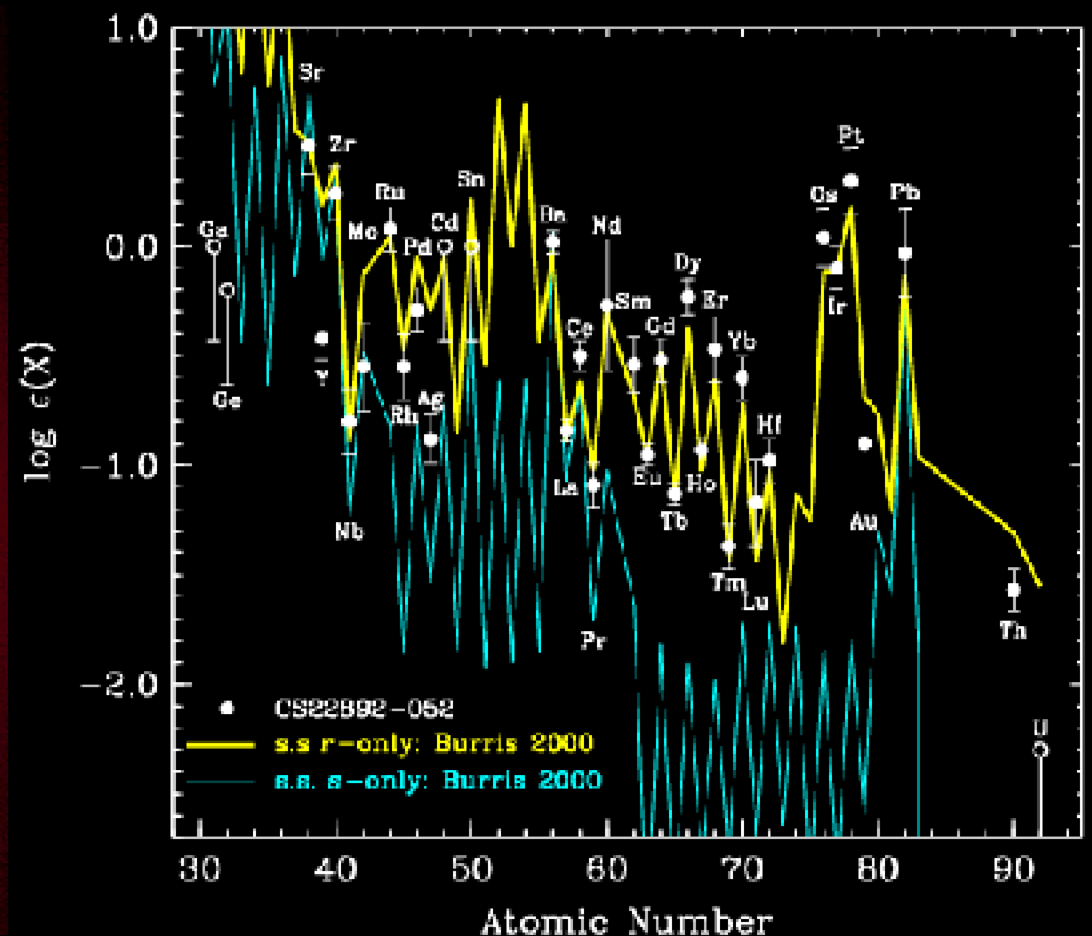
- Effective Field Theories
  - QCD is hard!
  - Remove (integrate out) the high-energy degrees of freedom
  - Maintain consistency with the symmetries
  - Hadrons
  - Hyperons (Strange hadrons)
  - Bose condensates
  - Quarks

- Ab-initio Calculations
  - Green's Function Monte Carlo - zero temperature - near and below nuclear saturation density
  - Lattice Field Theory - small μ/T
  - Molecular Dynamics - Classical simulations at finite density and temperature
  - Path Integral Monte Carlo - finite density for sufficiently large temperature with bosonic and fermionic statistics - capture the physics of the liquid-gas phase transition (A.S. and J. Carlson)

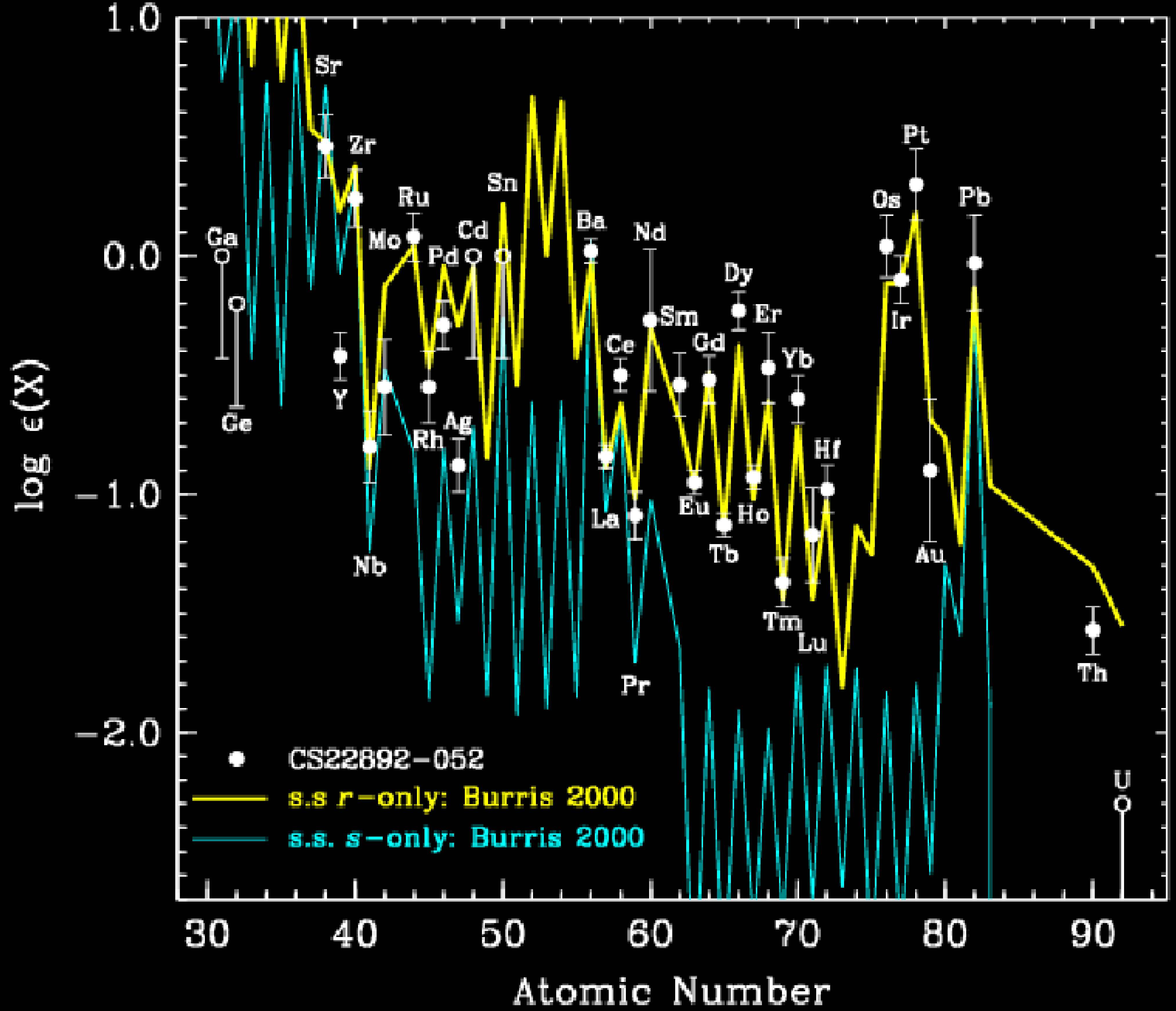
Nucleosynthesis of Heavy Nuclei

- For heavy-nuclei: r- and the s-process "rapid" and "slow" neutron capture
- The r-process environment is neutron-rich with high entropy, while the s-process occurs in colder, proton-rich regions
- The fundamental assumption - the r-process is universal
- Subtract s-process contributions from the solar abundances - scaled r-process distributions
- While we know quite a bit about the necessary conditions - what is the astrophysical site?
- Supernova neutrino-driven winds and neutron star mergers



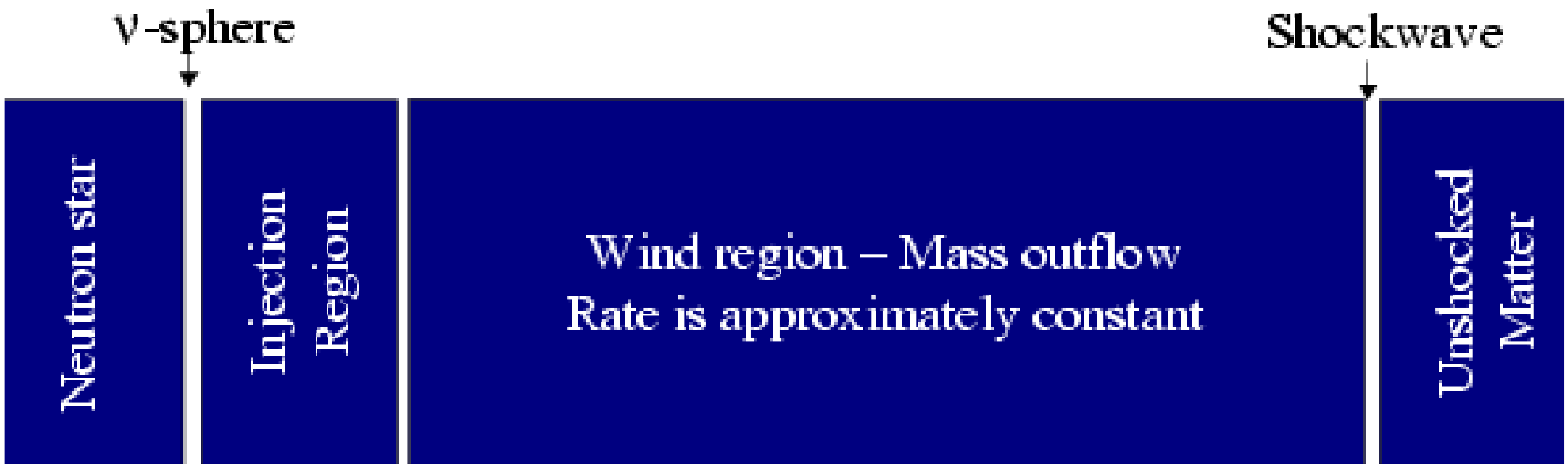


Nucleosynthesis of Heavy Nuclei



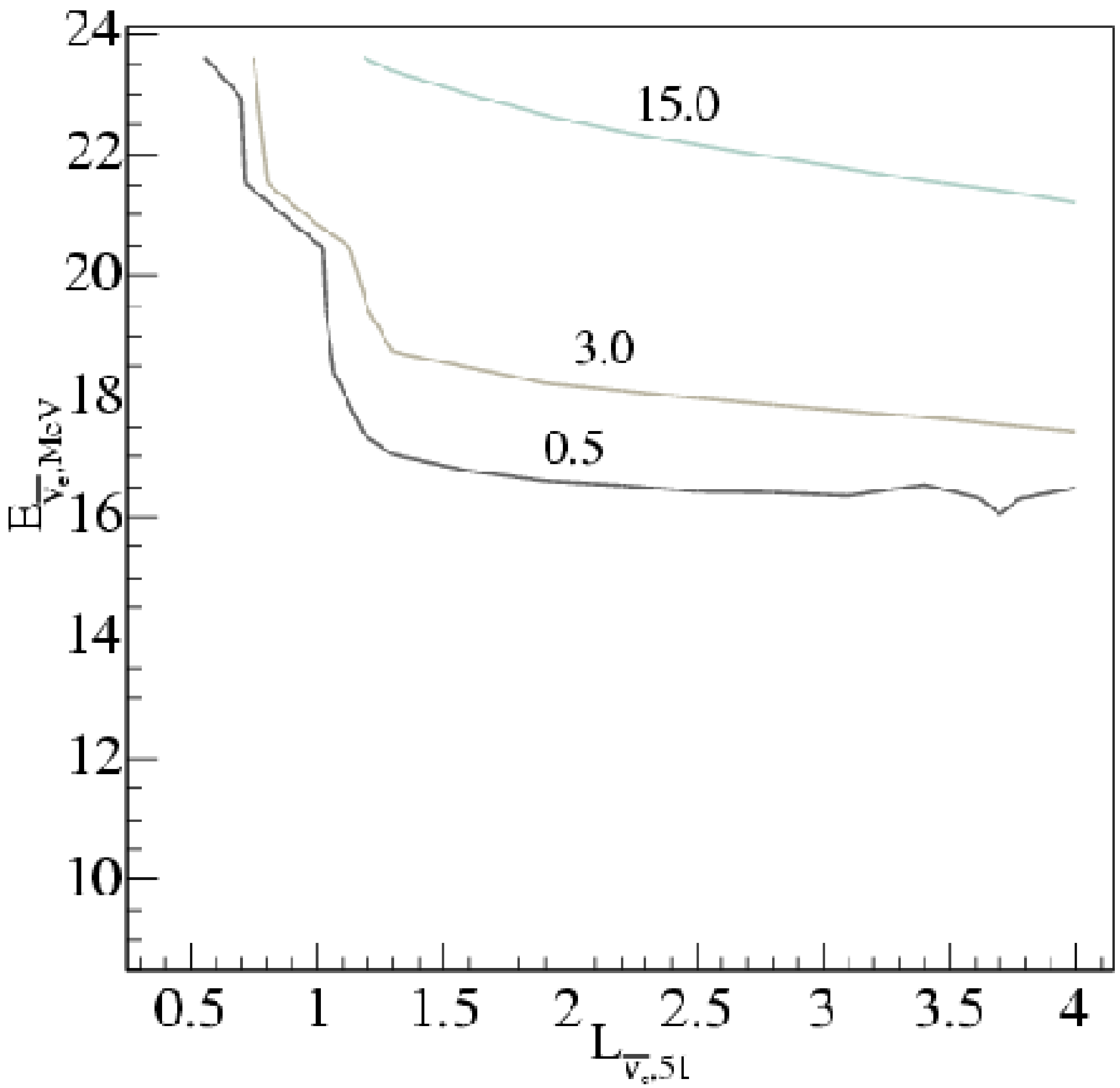
The Neutrino-Driven Wind

- Neutrino-driven wind occurs in the region between the newly-born neutron star and the exiting shockwave
- Wind region characterized by a constant mass outflow rate
- Describe an injection region, where mass outflow increases to create the wind (A.S. and Y. Qian)

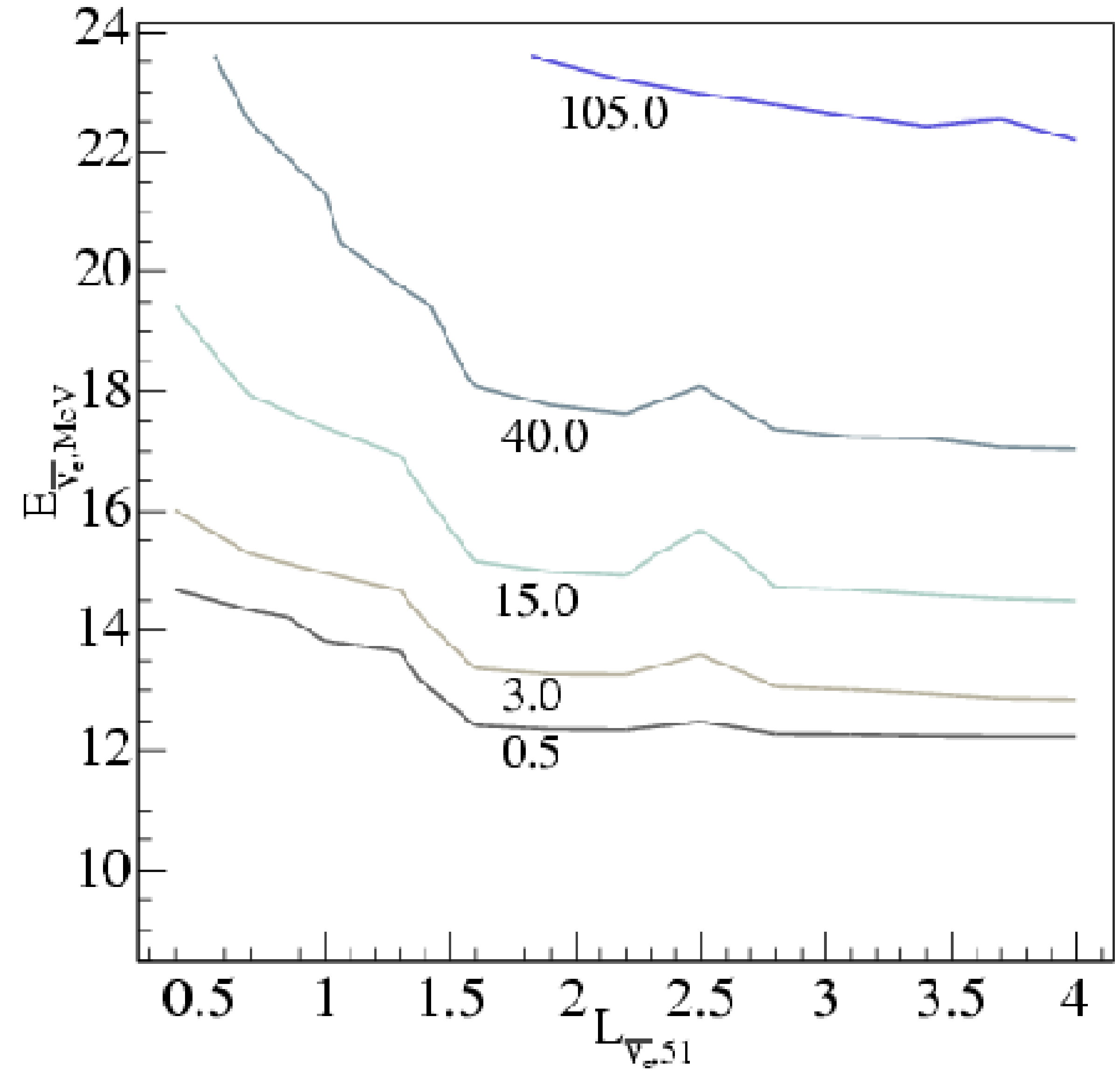


The r-Process Problem

- Neutrino-driven winds in supernovae - usually calculated in two steps: $(M, R, L_\nu, \langle E_\nu \rangle) \rightarrow (S, \tau_{dyn}, Y_e) \rightarrow (N/S)$
- First calculation to connect the properties of the proto-neutron star (M, R, neutrino luminosity, average neutrino energies) directly to N/S (A.S. and Y. Qian)
- The release of neutrinos plays an important role in providing viable nucleosynthesis



Neutrinos trapped



Neutrinos are free

The r-Process Problem

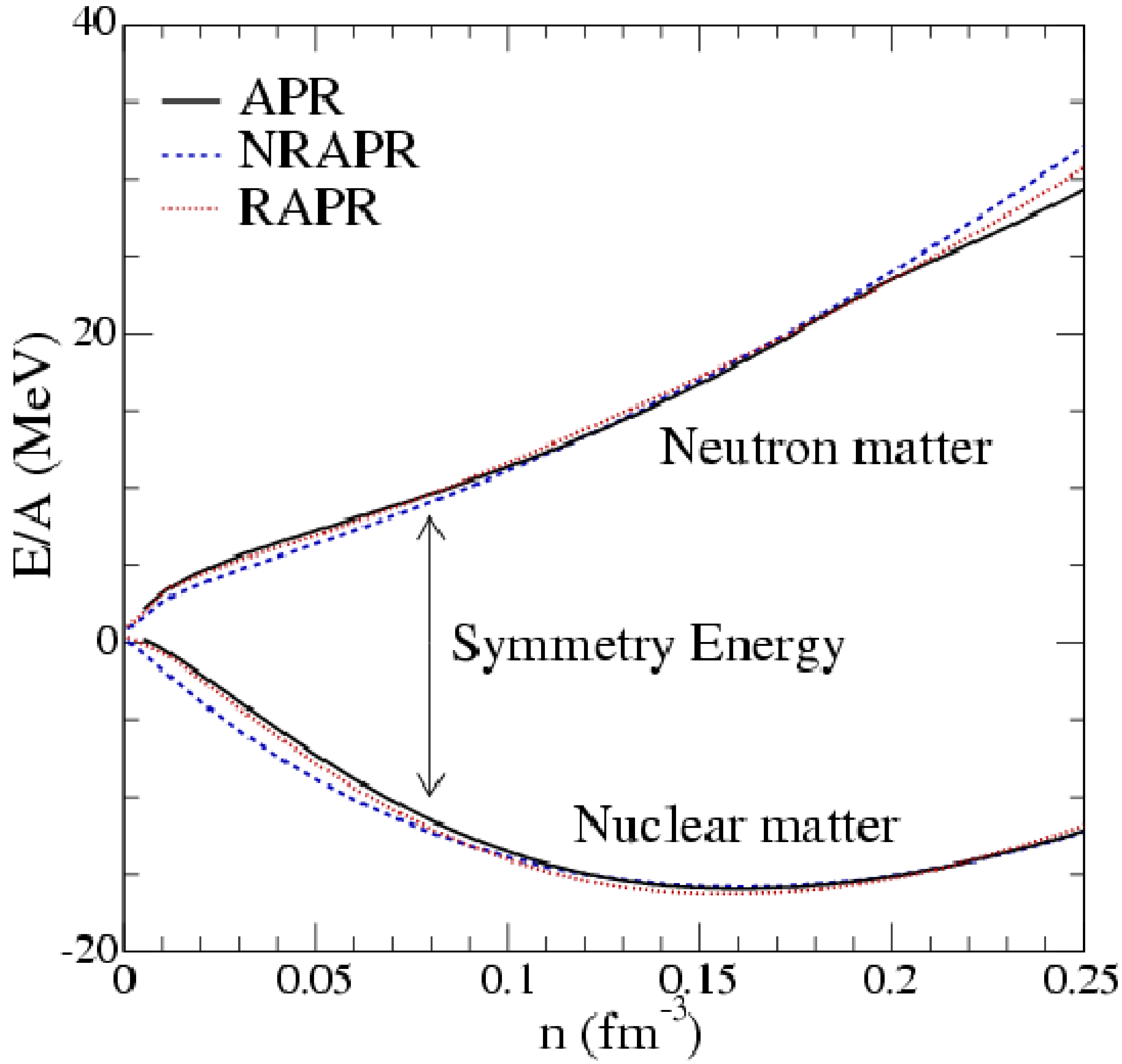
- Supernova winds do not produce the requisite conditions - New physics?
  - Neutrino mixing physics
  - Supernova asymmetry
  - Convection
  - Recent data suggests that there might be deviations from universality - two types of "r-process" events

The Nuclear Physics of Nucleosynthesis

- Nuclear structure and nuclear reaction rates
- How to get from N/S to the r-process distribution
- RIA
- The electron fraction depends on the symmetry energy

The Influence of the Nuclear Symmetry Energy

- The symmetry energy is the size of the energy cost of creating an asymmetry between the number of neutrons and protons
- Note that the pressure (at zero T) is related to the derivative of the energy per baryon (E/A)



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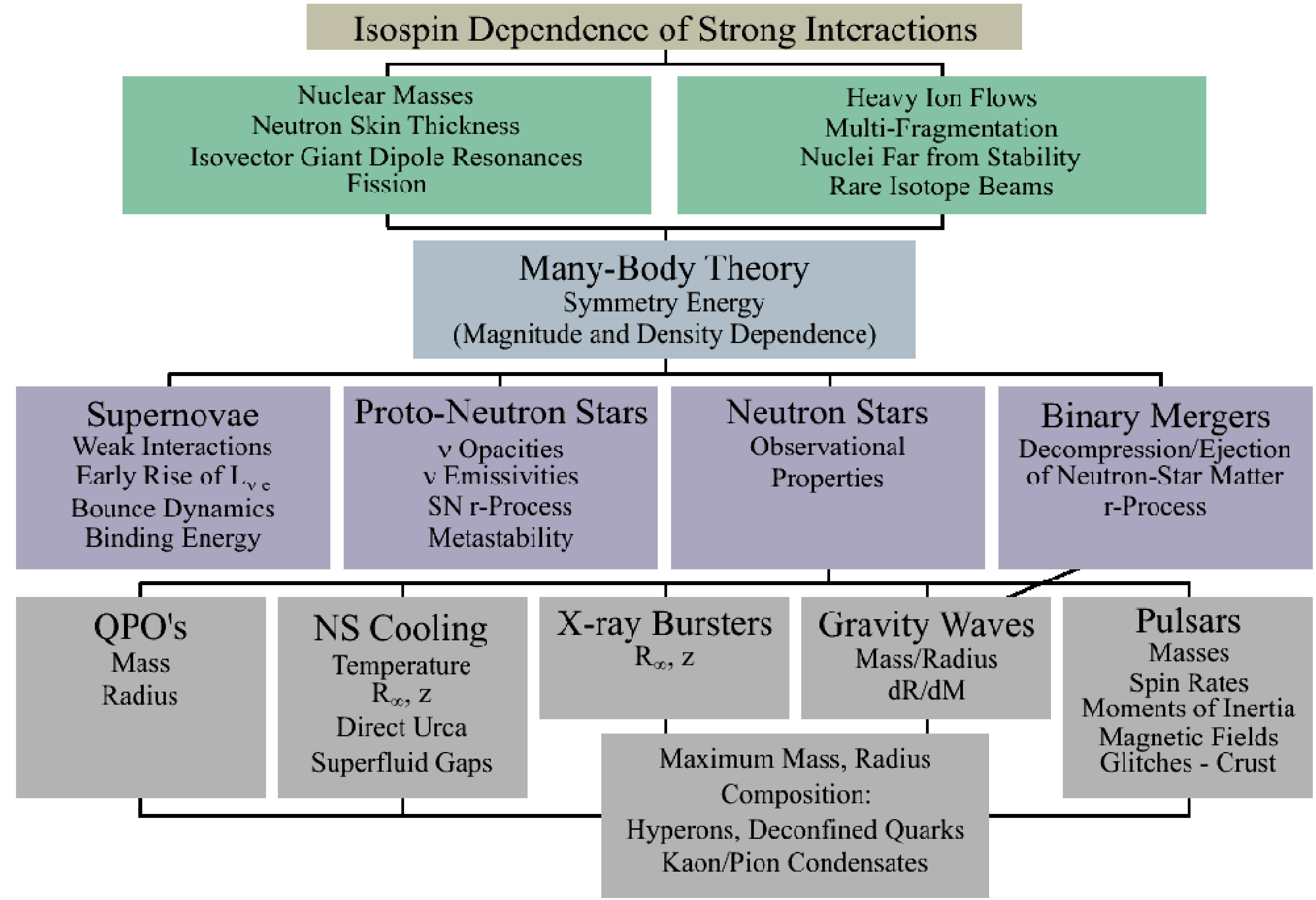
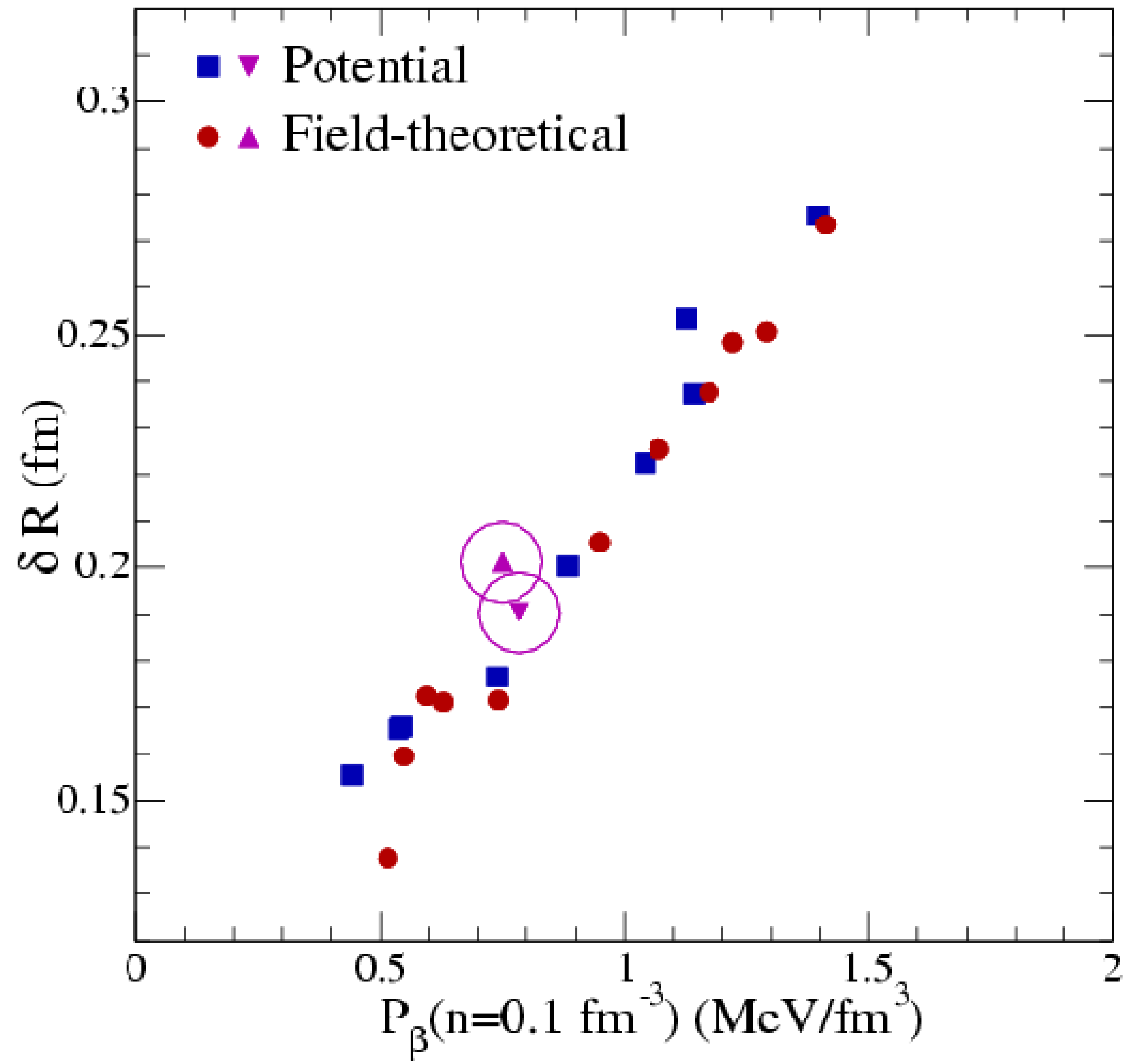


The Skin Thickness of Lead

- The "neutron skin thickness" is the difference between the neutron and proton rms radii
- This number is tightly correlated to the pressure of neutron matter at a particular density
- The pressure of neutron matter is almost entirely determined by the symmetry energy
- The neutron skin thickness of Pb^{208} will be measured accurately at Jefferson Lab



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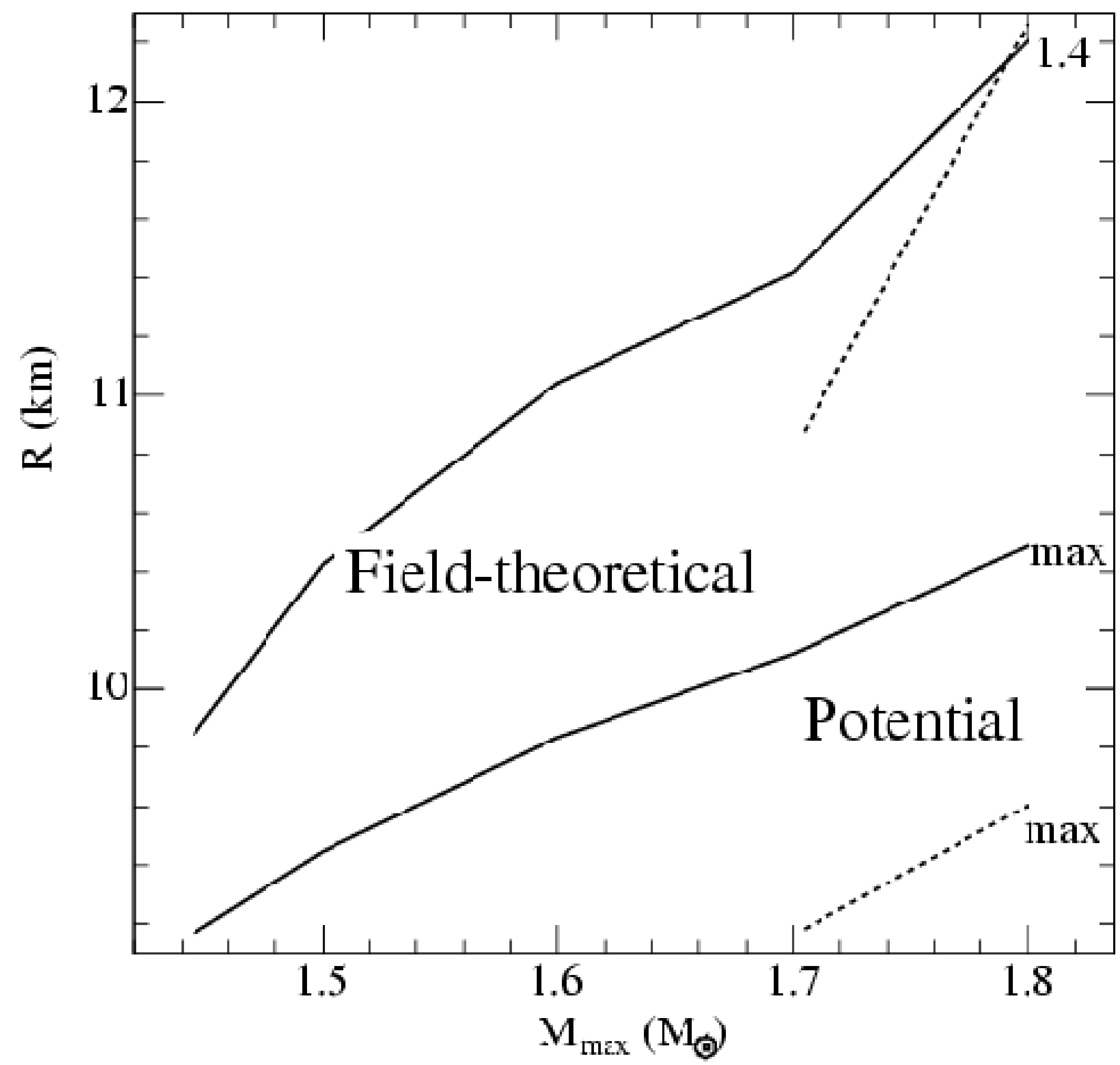
Small Neutron Star Radii

- What is the smallest radius for a "normal" neutron star?
- Use mean-field theory to give a wide range of equations of state which meet the empirical facts
  - Properties of laboratory nuclei
  - Properties of saturated nuclear matter
  - Neutron star properties
- Largest accurate mass measurements used to be 1.44 $M_\odot$
- Recent neutron star mass measurements suggest masses at least 1.9 - 2 $M_\odot$



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Summary

- The synthesis of nuclear physics and astrophysics to describe these astrophysical objects is answering fundamental questions about how the universe works
    - Properties of extreme matter
    - r-Process nucleosynthesis
    - The symmetry energy
- This synthesis is creating new answers to how astrophysical processes operate and new answers about how nuclear forces operate.